SMAR 2019

Shear strengthening of masonry walls with Flax Textile Reinforced Mortar composite systems

Giuseppe FERRARA [1,2], Carmelo CAGGEGI [2], Enzo MARTINELLI [1], Aron GABOR [2]
[1] University of Salerno, Fisciano (SA), Italy
[2] University Claude Bernard Lyon 1, Villeurbanne, France

Contact e-mail: giferrara@unisa.it

ABSTRACT: Masonry constructions built in the past decades in earthquake-prone areas are generally characterised by significant levels of seismic vulnerability. Therefore, strengthening and retrofitting of those constructions is more and more perceived as a major societal challenge, also in the light of damages and casualties induced by recent seismic events, such as those occurred in central Italy. Several techniques are nowadays available for enhancing seismic safety of existing masonry structures. Among them, the use of composite materials is widely accepted as one of the most convenient options. Besides the first generation of composites materials, based on polymeric matrix, a new type of materials adopting an inorganic matrix is attracting a growing interest within the scientific and technical community: these materials are often referred to as Textile Reinforced Mortars (TRM).
This paper reports the results of a series of tests carried out with the aim to investigate the potential of a novel type of TRM in enhancing the in-plane shear capacity of masonry walls. Specifically, the TRM system under consideration is based on adopting a flax fabric as internal reinforcement. Therefore, it is characterised by high sustainability properties and a mechanical behaviour that has been investigated within a companion paper. The experimental activity confirms the potential in the use of plants fibres based composite systems as reinforcement of masonry elements. In comparison with unreinforced walls tested as reference, the peak load doubled. Moreover, the use of Flax-TRM led to a ductile behaviour never shown in unreinforced walls typically characterised by a brittle response. The research study paves the way for further investigation aimed at both identifying the performance under different load configuration and improving the composite material response.

1 INTRODUCTION

Textile Reinforced Mortar (TRM) composite systems are gaining consensus as one of the most effective retrofitting techniques, as they offer several advantages, such as vapour permeability, compatibility with the substrate, reversibility of the retrofitting system, time and cost of installation (D'Ambrisi et al. 2013). Several studies have been carried out with the aim to characterise the mechanical behaviour of TRM systems by adopting different kinds of synthetic and industrial textiles, such as PBO, carbon, basalt and glass (Caggegi et al. 2017; Lignola et al. 2017). Moreover, replacing the aforementioned industrial textiles with alternative ones made of plant fibres, such as flax, curaua, sisal, jute, coir or hemp, appears as a promising option to improve sustainability of TRM systems (Ferreira et al. 2017; Ferrara[1] et al. 2019; Codispoti et al. 2015; Ferrara[3] et al. 2019). However, further investigations are needed to deepen knowledge about both mechanical performance and durability-related aspects.

Therefore, this paper presents the results of an experimental study aimed to investigate the shear capacity of masonry walls externally strengthened by TRM composite systems reinforced with flax textile. To this purpose two strengthening configurations, characterised by different amount of textile, have been considered to strengthen clay-brick walls subjected to diagonal compression tests; moreover, unstrengthened walls have been tested as reference specimens.

2 MATERIALS AND METHODS

2.1 Materials

2.1.1 Masonry substrate

The masonry substrate consists of a single-wythe wall characterised by 16 courses separated by 1 cm joints. The employed clay bricks, 250 mm long, 120 mm wide and 55 mm thick, are characterised by a compression strength of 17.89 MPa (Co.V. 4.9%) and a tensile strength of 2.46 MPa (Co.V. 11.4%) (de Felice et al. 2015). A low resistance natural hydraulic lime-based mortar is adopted for the joints to reproduce a wall whose strength may be representative of existing buildings. It is characterised by a volumetric composition of 2 parts of binder, 4 parts of sand, 1.3 parts of water. Mortar specimens, prismatic in shape (40 x 40 x 460 mm^2), were sampled the wall casting and tested after 28 days in accordance with the EN 196-1 (1994) exhibiting a flexural strength of 0.94 MPa (Co.V. 19.82%) and a compression strength of 4.11 MPa (Co.V. 20.51%).

2.1.2 Strengthening system

The walls are externally strengthened by means of a TRM composite system. It consists of a natural hydraulic-based mortar matrix reinforced by a natural textile. The latter is a woven fabric in which the flax threads, characterised by smaller entwined filaments, are arranged to have the same strength in the two orthogonal directions (Figure 1). The main physical and mechanical properties of the flax fabric are shown in Table 1 (Ferrara[2] et al. 2018).

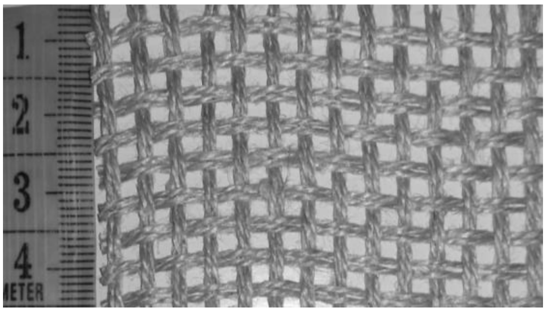

Figure 1. Flax textile.

The matrix of the TRM system is made of a pre-mixed mortar in which aggregates characterised by the maximum size of 2.5 mm and the binder is natural hydraulic lime. The amount of water is 19% in weight of the pre-mixed powder. A hydraulic lime-based mortar, rather than a cement-based one, has been utilised because its properties are closer to the materials usually employed in the construction of historical masonry buildings. During the implementation of the strengthening system on the wall prismatic samples of mortar (40 x 40 x 160 mm^3) were performed and tested after 28 days of curing in ambient conditions according to the EN 196-1 (1994). The flexural and compression strengths, evaluated as a mean of all the samples tested, are respectively equal to 3.13 MPa (Co.V. 12.55%) and 11.13 MPa (Co.V. 8.23%).

Table 1. Geometric and mechanical properties of the flax fabric.

	Mean	Co.V. (%)
filament diameter (μm)	16.78	29.64
density (g/cm^3)	1.19	3.29
linear density (Tex)	302	15.27
n° threads/cm	4.3	-
thread cross-section (mm^2)	0.25	16.62
Young's Modulus (GPa)	9.36	10.67
Strain to failure (%)	3.85	12.94
Tensile strength (MPa)	353.72	11.53

The mechanical behaviour of the composite system has been investigated in a previous research study (Ferrara et al 2018) by means of tensile tests performed on TRM coupons, reinforced with either one or two layers of flax fabric, in accordance to RILEM TC 232-TDT recommendations (2016). The specimens, reinforced either with one or two layers of flax fibres, exhibited a tensile strength respectively of 1255 N (Co.V. 9.58%) and 2430 N (Co.V. 7.49 %).

The strengthening system has been applied over the entire surface of both sides of the walls. After spreading a first layer of mortar on the masonry substrate (Figure 2, a, b), the flax fabric has been deployed on it by exerting a light pressure to allow the mortar to properly penetrate within the grid spaces of the textile (Figure 2, c). The same procedure has been repeated in case of implementation of the second layer of textile by ensuring that a ply of mortar is placed between the different textile layers. Consequently, the last layer of mortar was applied by smoothing the entire surface (Figure 2, d).

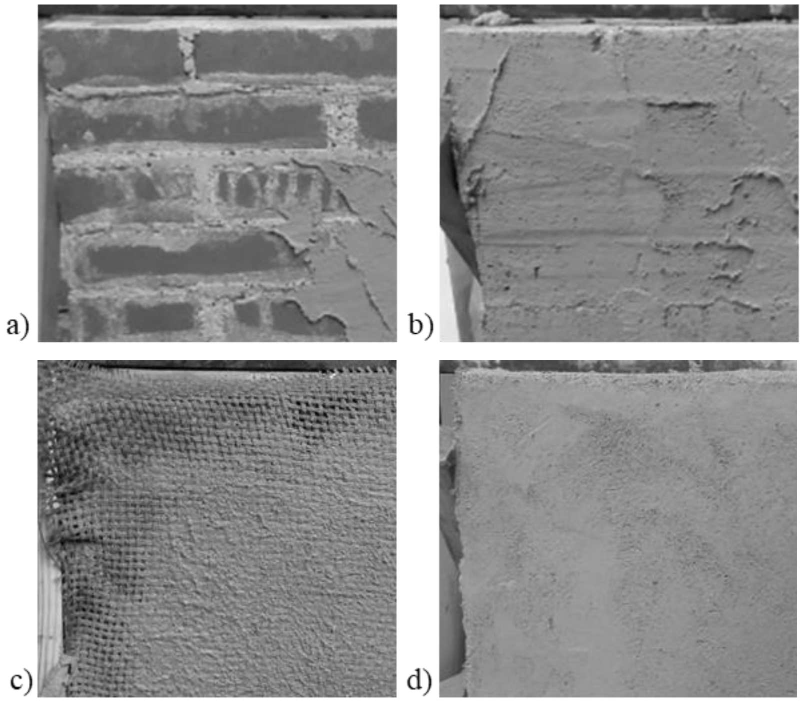

Figure 2. Implementation of the strengthening system: a) unstrengthened wall surface; b) application of the first ply of mortar; c) application of the flax textile; d) application of the second ply of mortar.

2.2 Methods

Masonry walls strengthened with Flax TRM composite systems have been tested under diagonal compression with the aim to investigate the influence of the external composite layers on the resulting shear capacity of the walls. To this purpose, unstrengthened walls have been tested to get a reference behaviour to compare with the mechanical response of strengthened walls.

Two strengthening configurations, respectively characterised by one and two plies of reinforcing flax fabric, have been considered in order to analyse the influence of the amount of textile on the global mechanical behaviour.

Three series of specimens were realised:

- *UnStrengthened Walls* (USW): the series consists of three wall coupons (100x100x12 cm^3) performed without the application of the strengthening composite system (Figure 3a);
- *Strengthened Walls with 1 flax textile Layer* (SW-1L): the series consists of three wall coupons (100x100x12 cm^3) externally strengthened on both the side by a Flax TRM composite system characterised by one ply of fabric and a thickness of 5 mm (Figure 3b);
- Strengthened Walls with 2 flax textile Layers (SW-2L): the series consists of three wall coupons (100x100x12 cm^3) externally strengthened on both the side by a Flax TRM composite system characterised by two plies of fabric and a thickness of 8 mm (Figure 3c).

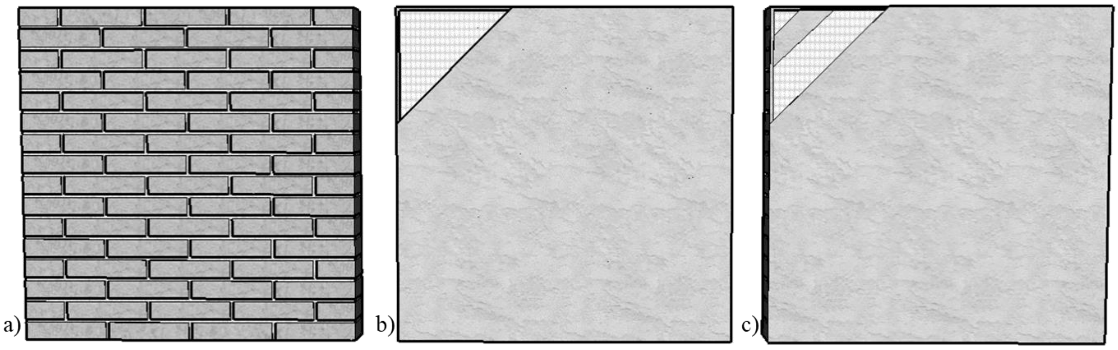

Figure 3. a) USW specimen; b) SW-1L specimen; c) SW-2L specimen.

The mechanical behaviour of unstrengthened and strengthened walls was investigated on wall coupons (100 cm x 100 cm x 12 cm).

Diagonal compression tests, performed 28 days after the walls have been strengthened, have been carried out by placing the coupons so that their diagonals are aligned along the vertical and horizontal directions. The tests have been carried out in displacement control, with a rate of 1 mm/min, by applying the force along the vertical direction.

According to the RILEM recommendations (1994), to reduce the local effects of the directly loaded area, two steel vee blocks were placed at the two corners of the vertical direction by means of a cement mortar covering a length of 15 cm on each side of the wall (Figure 4b). Two displacement transducers have been placed on one side of the wall to record during the test the elongation (in the horizontal direction) and the shortening (in the vertical direction) of a segment 1 meter long (Figure 4a).

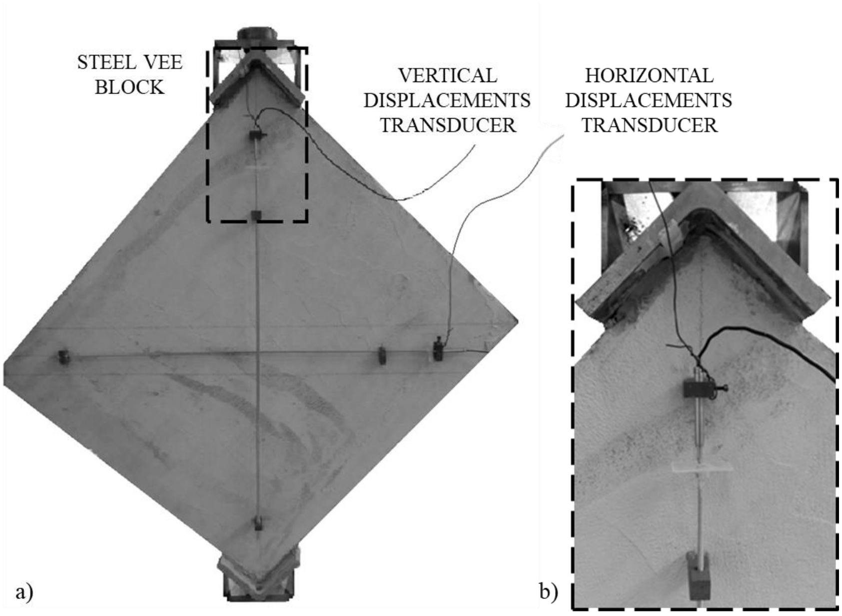

Figure 4. a) Diagonal compression test set-up; b) Particular of the vertical displacement transducer and of the steel vee block.

3 RESULTS AND DISCUSSION

The results of the diagonal compression tests are presented in terms of Load vs Horizontal/Vertical displacements (Figure 4). The unstrengthened walls (*USW*) showed an elastic behaviour with a brittle failure following the achievement of the maximum load.

Failure occurs with a pseudo-vertical crack along the tensile principal stress direction (Figure 5a). The walls externally strengthened by TRM systems either with one ply (*SW-1L*) or two plies (*SW-2L*) of flax textile showed an elastic behaviour up to the achievement of the maximum load followed by a post-peak phase. The drop of the load after the elastic branch is due to the tensile failure of the substrate masonry and the mortar matrix of the TRM reinforcing composite system. The post-peak phase is characterised by a gradual rupture of the flax textile along the cracks (Figure 5c). The latter are mainly distributed vertically in a zone in the middle of the wall representing the area in which the tensile stresses are concentrated (Figure 5d). Only one specimen of the *SW-1F* series exhibited a failure mode characterised by the debonding of the TRM system from the masonry substrate (Figure 5b). This behaviour may be due to a not good implementation of the reinforcement during the casting. According to the standard ASTM E519-2 (2003) the values of the shear stress, τ_{peak}, and of the shear strain, γ_{peak}, corresponding to the peak load have been evaluated for each specimen (Table 2). Moreover, in order to better quantify the influence of the amount of reinforcement on the mechanical response of the walls the area underlying the Load-Vertical displacement curves was chosen as a parameter representative of the rupture energy of the specimens.

The values of the elastic energy, E_{el}, computed as the area underlying the Load-Vertical displacement curves in the elastic phase, and of the energy dissipated during the post-peak phase, E_{in}, computed for each specimen are shown in Table 2. Specifically, E_{in}, represents the area underlying the Load-Vertical displacement curve in the region between the displacement corresponding the maximum load, and the displacement corresponding to a force equal to the 30% of the maximum load.

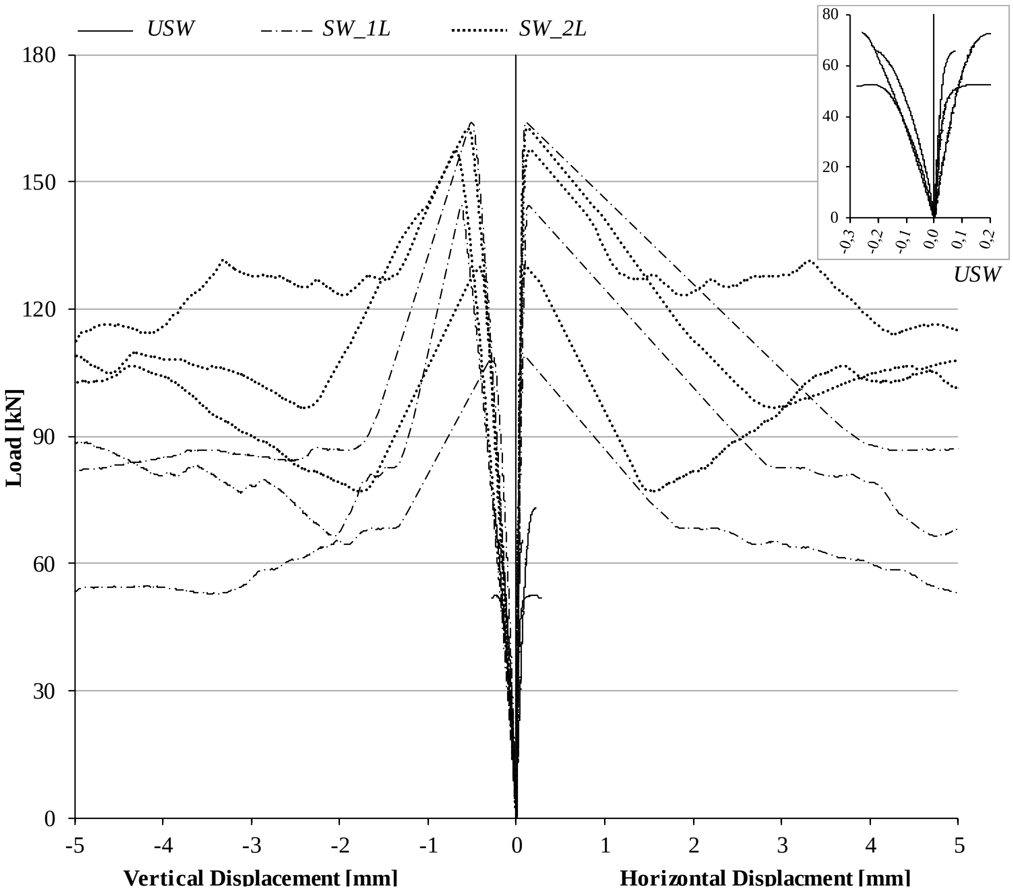

Figure 4. Load-Displacement curves of *USW*, *SW-1L* and *SW-2L* series of specimens.

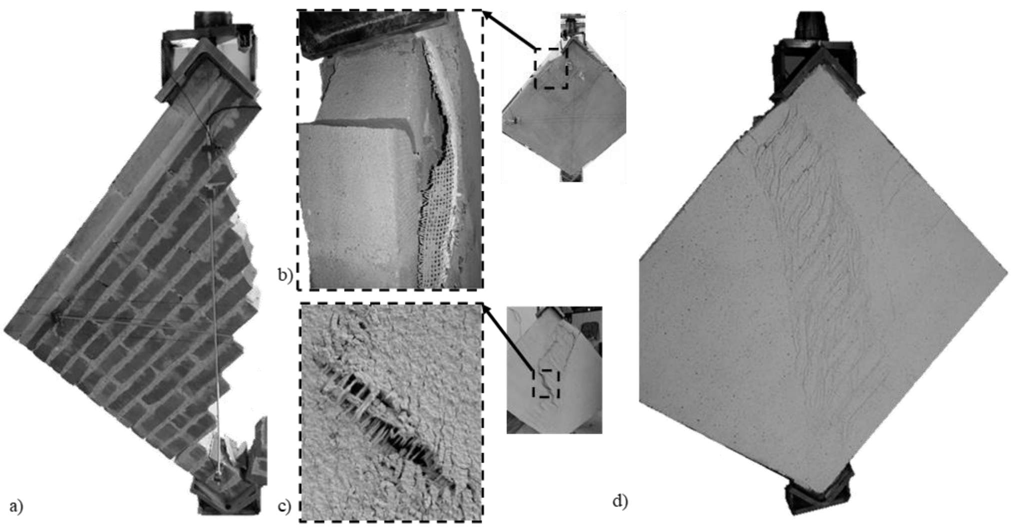

Figure 5. Failure mode detail of specimens: a) USW-2; b) SW-1F-1; c) SW-2F-1; d) SW-2F-1.

In terms of peak load, a significant increase is observed in the externally strengthened wall with respect to the reference specimens. Specifically, the main values of maximum strength increased of the 118% in case of the *SW-1L* specimens, and of the 136% in case of the *SW-2L* specimens. Furthermore, the externally strengthened walls exhibited a post-peak phase completely absent in the case of the *USW* series. The mean value of the post-peak energy, E_{in}, concerning the specimens externally strengthened by the TRM composite systems reinforced by two plies of flax textile (*SW-2L*) is more than two times higher than the main value concerning the *SW-1L* series. This aspect confirms that un higher amount of textile reinforcement provides a greater main strength of the wall after the crack of the substrate has occurred.

Table 2. Test parameters concerning *USW*, *SW-1L* and *SW-2L* series of specimens

Specimen	P_{peak} (kN)	τ_{peak} (MPa)	γ_{peak} (%)	E_{el} (J)	E_{in} (J)
USW-1	65.50	0.39	0.03	8.83	-
USW-2	73.13	0.43	0.05	10.90	-
USW-3	52.50	0.31	0.05	10.56	-
Mean	63.71	0.38	0.04	10.10	-
Co.V. (%)	16.37	16.37	27.12	11.02	-
SW-1L-1	164.00	0.97	0.06	47.82	880.66
SW-1L-2	144.50	0.85	0.07	50.64	1552.02
SW-1L-3	108.88	0.64	0.04	18.91	1019.15
Mean	139.13	0.82	0.06	39.12	1150.61
Co.V. (%)	20.09	20.09	34.21	44.88	30.81
SW-2L-1	162.63	0.96	0.07	53.96	1730.06
SW-2L-2	130.00	0.77	0.05	30.64	2964.03
SW-2L-3	157.50	0.93	0.08	65.01	3221.61
Mean	150.04	0.88	0.07	49.87	2638.57
Co.V. (%)	11.69	11.69	22.10	35.18	30.22

4 CONCLUSIONS

The study concerns an experimental investigation of the shear strength of masonry walls externally strengthened by TRM composite systems performed using flax textile as reinforcement. The main findings of the research study are summarised as follow:

- the implementation of the strengthening TRM system significantly affect the mechanical response of the walls with an increase of the shear strength of the 118% and 136% respectively observed in the *SW-1L* and *SW-2L* series of specimens;
- the main failure mode of the strengthened walls was characterised by a gradual rupture of the flax thread placed along the principal tensile stress direction, without significantly involving adherence crisis at the fabric-to mortar or TRM-to-masonry interface surfaces;
- the failure mode observed confirms the efficiency of the TRM composite system adopted characterised by a lime-based mortar matrix reinforced by flax textile;
- the externally strengthened walls exhibited a post-peak phase completely absent in the unstrengthened walls, highlighting the efficiency of the strengthening system also in view of applications in masonry seismic retrofitting interventions;
- the post-peak behaviour concerning the walls strengthened by the TRM system characterised by 2 plies of flax textile (*SW-2L*) is characterised by a mean value of the dissipated energy more than two times higher of that one concerning the *SW-1L* series.

The study shows the good mechanical performances of flax textile as reinforcement in TRM composite systems. Further investigations on the durability and mechanical behaviour of this kind of composite will be useful in the framework of preservation of masonry structures.

5 ACKNOWLEDGMENTS

The first Author's Ph.D. scholarship is granted by the Italian Ministry for Education, University and Research (MIUR) as part of the programme "*Dottorati Innovativi a caratterizzazione industriale*" funded by the European Union (Structural Funding ERDF-ESF for "Research and Innovation" 2014-2020), whose financial support is gratefully acknowledged. The financial support for the first Author's mobility is provided by UCBL as part of the "*soutien mobilité école doctorale MEGA*". Moreover, the Authors gratefully acknowledge INNOVATIONS s.r.l. for providing the materials tested in the experimental research.

6 REFERENCES

ASTM E519-2, 2003. Standard Test Method for Diagonal Tension (Shear) in Masonry Assemblages. *ASTM Committee C15 on Manufactured Masonry Units*.

Caggegi C, Carozzi FG, De Santis S, Fabbroncino F, Focacci F, Hojdys L, Lanoye E, Zuccarino L, 2017. Experimental analysis on tensile and bond properties of PBO and aramid fabric reinforced cementitious matrix for strengthening masonry structures, *Composites Part B* 128 100-119.

Codispoti R, Oliveira DV, Olivito RS, Lourenço PB, Fangueiro R, 2015, Mechanical performance of natural fibr-reinforced composites for strengthening of masonry, *Composites Part B*, 77 74-83.

D'Ambrisi A, Focacci F, Caporale A, 2013, Strengthening of masonry-unreinforced concrete railway bridges with PBO-FRCM materials, *Composite Structures*, 102 193-204.

de Felice G, Aiello MA, Bellini A, Ceroni F, De Santis S, Garbin E, Leone M, Lignola GP, Malena M, Mazzotti C, Panizza M, Valluzzi MR, 2015, Experimental characterization of composite-to-brick masonry shear bond, *Materials and Structures*, 49(7):2581-96.

EN 196-1:1994. Methods of testing cement – Part 1: Determination of Strength. *European Committee for Standardization*.

Ferrara[1] G, Coppola B, Di Maio L, Incarnato L, Martinelli E, 2019. Tensile strength of flax fabrics to be used as reinforcement in cement-based composites: experimental tests under different environmental exposures, *Comp Part B*, 168 511-523.

Ferrara[2] G, Martinelli E, 2018, Tensile behaviour of Textile Reinforced Mortar composite systems with flax fibres, *Proc. of the 12th fib International PhD Symposium in Civil Engineering Aug 29 to 31*, Czech Technical University in Prague, Prague, Czech Republic.

Ferrara[3] G, Pepe M, Martinelli E, Toledo Filho RD, 2019, Influence of an impregnation treatment on the morphology and mechanical behaviour of flax yarns embedded in hydraulic lime mortar, *Fibers*, 7, 30.

Ferreira SR, de Andreade Silva F, Lima PRL, Toledo Filho RD, 2017, Effect of hornification on the structure, tensile behaviour and fiber matrix bond sisal, jute and curaua fiber cement based composite systems, *Construction and Building Materials*, 139 155-161.

Lignola GP, Caggegi C, Ceroni F, De Santis S, Krajewsky P, Lourenço PB, Morganti M, Papanicolaou C, Pellegrino C, Prota A, Zuccarino L, 2017. Performance assessment of basalt FRCM for retrofit applications on masonry, *Comp Part B*, 128 1-18.

RILEM LUMB6, 1994, Diagonal tensile strength tests of small wall specimens, *RILEM recommendations for testing and use of constructions materials*, 488-9.